

The Effect of Concentration Change on Heat Transfer in Drag-Reducing Solutions

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Abstract

Worm-like surfactant micelles are already being used to efficiently and inexpensively transport fluids by reducing the effect of pressure loss in turbulent flow. However, these solutions are not easily used in systems that require changes in temperature since these micelles also reduce the effect of heat transfer. It has been found that for a certain aqueous drag-reducing solution that combines zwitterionic and cationic surfactants, adding solvent to the solution can cause these micelles to precipitate. When these micelles have precipitated out of solution, they are no longer able to reduce drag and heat transfer.

Therefore, for this research project, the concentration of drag-reducing solutions in a lab-scale piping system was changed in order to test whether or not dilution and re-concentration are viable methods for turning drag and heat transfer reduction on and off. To do this, a zwittercationic solution at a concentration nearly low enough to exhibit dilution precipitation was tested for drag reduction and heat transfer reduction in a recirculating flow system. The solution was diluted and tested until drag and heat transfer reduction were no longer evident. The solution was brought back to its original concentration by using a reverse osmosis membrane to take out water. As the solution was re-concentrated, it was tested to see if drag and heat transfer reduction came back.

Graphs showing the drag reduction and heat transfer reduction in comparison to water at varying Reynolds numbers were produced for the zwittercationic solution used in this experiment. These graphs were then analyzed to determine if concentration change was a feasible method for reducing drag with little to no heat transfer reduction. The graphs showed that concentration change is a legitimate method for improving heat transfer in this drag-reducing solution. However, any success with this concentration change method was largely dependent on time between dilution and re-concentration stages and ignoring potential membrane fouling that would occur during long-term use, making this an unlikely method for improving heat transfer in re-circulating flow systems in the near future.

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1 Introduction

1.1 History of Drag Reduction

In turbulent fluids, it has been observed that certain additives in a carrier fluid can cause a reduction in pressure loss due to friction without forcing the flow behavior to become laminar [1]. This phenomenon is known as turbulent drag reduction [1]. Friction losses in turbulent flows were first observed by Forrest and Grierson in 1931 when they studied the friction associated with pumping paper stock [2]. In 1945, drag reduction was observed again when Mysels discovered that adding a 2:1:1 mixture of the aluminum soap of coconut oil acid, aluminum naphthenate, and aluminum oleate to gasoline reduced the amount of pressure required to pump it through pipes [3]. In 1948, Toms observed that polymers with high molecular weights could also be used for the purpose of drag reduction [4]. Due to the research that Toms performed, drag reduction is also sometimes called the Toms Effect [1]. Since these first reports, the studies regarding drag reduction have increased, and the most commonly used additives are high molecular weight polymers and surfactants.

1.2 Drag and Heat Transfer Reduction Fundamentals

For the purposes of fluid transport, drag is the decrease in pressure caused by wall shear stress and turbulence at sufficiently high Reynolds numbers. The additives that have been found to cause drag reduction essentially decrease the magnitude of the pressure drop that occur from the wall shear stress and turbulence by as much as 90% [1]. Drag reduction is mathematically defined as the percent decrease in the friction factor between a drag reducing solution and the solvent alone when compared at the same volumetric flow rate, as shown in Equation 1.

$$DR\% = \frac{f_{solvent} - f_{measured}}{f_{solvent}} * 100\% \quad (1)$$

It has been found that drag reducing solutions also tend to have lower convective heat transfer coefficients due to lower radial turbulence [5]. This phenomenon is called heat transfer reduction, and it is mathematically defined as the percent decrease in the Nusselt number between a drag reducing solution and the solvent alone when compared at the same volumetric flow rate, as shown in Equation 2.

$$HTR\% = \frac{Nu_{solvent} - Nu_{measured}}{Nu_{solvent}} * 100\% \quad (2)$$

1.3 District Heating and Cooling

While drag reducing additives have already found value in applications such as reducing pumping costs in oil pipelines and increasing the range of the water used to fight fire in fire hoses, drag reducing additives could also potentially be useful for decreasing the pumping costs in district heating and cooling systems [6] [7]. Use of drag reducing additives in such systems would allow for water to be heated or cooled in one central location before cheaply being transported throughout city districts to heat or cool buildings as necessary. However, there are still a few barriers making this application difficult. To start, high molecular weight polymers can break down in turbulent flow over time, so they are not realistic additives for use in re-circulating district heating and cooling systems [1]. This limits the additives that could be used to primarily just surfactants. Second, these drag reducing additives also reduce convective heat transfer, which would make it difficult to add or remove heat from fluids used in district heating or cooling systems [5].

1.4 Surfactant Drag Reduction

Since high molecular weight polymers break down in re-circulating flow systems over time, this research only considers the use of surfactant drag reduction. Surfactants are unique in that they have both a hydrophobic tail and a hydrophilic head group in the same

molecule [1]. For this reason, when surfactants are in a polar solvent such as water, one favorable formation for the surfactants is a micellar arrangement so that the hydrophilic head groups are in contact with the water and the hydrophobic tails are not. At sufficient temperatures above what is called the Kraft point and at concentrations above a critical micelle concentration (CMC), surfactants are able to form these favorable micelle formations [1]. Furthermore, at low concentrations above the CMC, surfactants form micelles with either an ellipsoidal or spherical shape, but at higher concentrations, above CMC_{II} , the micelles begin to take on more of a rod-like, or wormlike, shape [1]. A general phase diagram showing how micelle formation is affected by concentration and temperature is shown in Figure 1 [1].

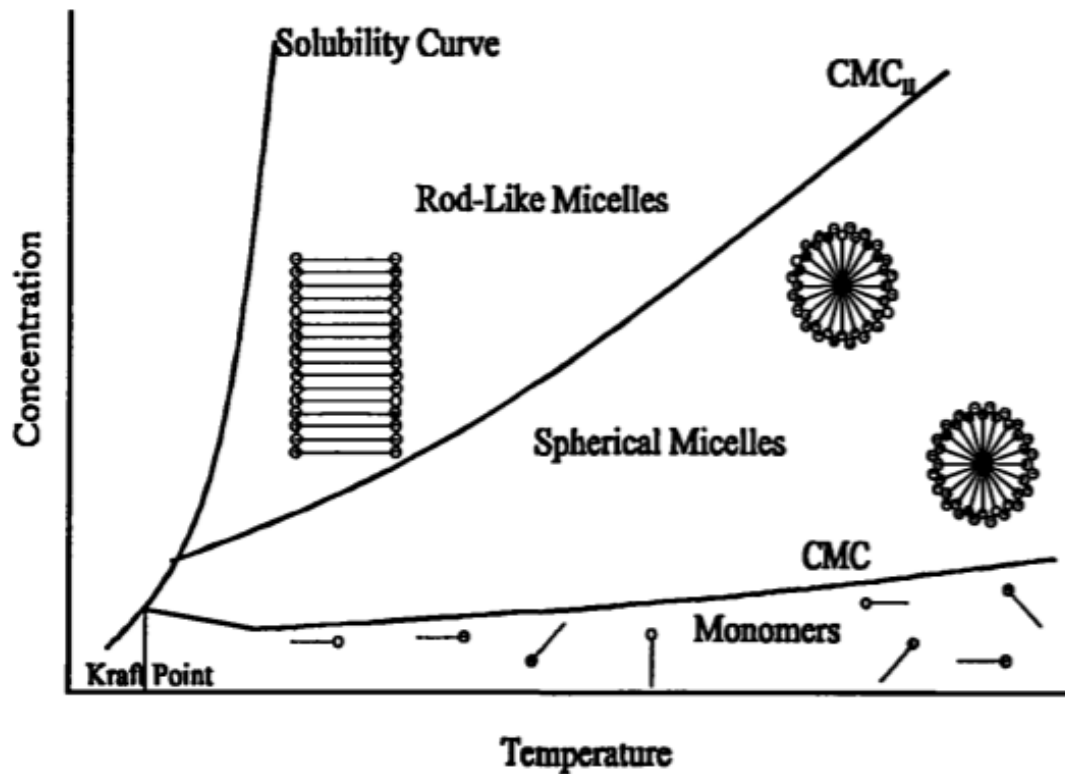


Figure 1: Micelle structure depends on concentration and temperature

The mechanism by which surfactant micelles cause drag reduction is poorly understood,

but it is understood that surfactant drag reduction is strongly correlated to micelles that have a worm-like shape [8]. For this reason, the research performed here focuses on surfactant solutions that are at a sufficiently high enough concentration to form wormlike micelles.

1.5 Types of Surfactant Mixtures

Surfactants are categorized by the type of charge that they carry. Ionic surfactants can either be cationic or anionic, meaning that they carry either a positive or negative charge, respectively. Zwitterionic surfactants have both a positive and a negative charge on the head of the molecule. There are also other types of nonionic surfactants. Mixed surfactant solutions are also typically stabilized with a counterion between headgroups that can aid the formation of micelles by minimizing electrostatic repulsion. This aids the formation of the micelle into the desired shape through changing the packing parameter by affecting the headgroup area [9]. The packing parameter is described by surfactant molecule volume, V , length of the hydrophobic tail, l , and the headgroup area, a , in Equation 3 [9].

$$p = \frac{V}{al} \quad (3)$$

As seen in Figure 2, the micelle shape goes from spherical, to rod-like, to branching and even forming a lamellar sheet as the packing parameter increases [9].




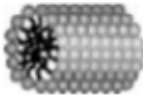

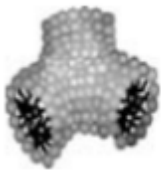

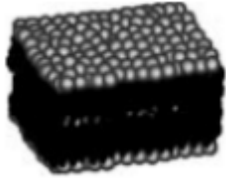
Micellar building blocks	Packing parameter	Surfactant shape	Micellar shape
Hemispherical endcap	$p < 1/3$		
Cylindrical section	$1/3 < p < 1/2$		
Threefold junction	$1/2 < p < 1$		
Lamellar sheet	$p \sim 1$		

Figure 2: Micelle Shape as Packing Parameter Changes

While many drag-reducing micelles are made of only cationic surfactants, some past experiments have used micelles that were developed by mixing surfactants with different electronic charges, such as zwitterionic and anionic mixed surfactant systems [10] [11]. Historically, there has not been much success in forming drag-reducing solutions from mixtures that combine zwitterionic and cationic surfactants, but recently, one such solution has been made by combining Arquad S-50, SB3-16, and sodium salicylate [12]. This solution has unique qualities which make it the solution of interest for this study.

1.6 Dilution Precipitation

This study seeks to propose and prove a method of precipitating zwittercationic wormlike micelles out of a solution in a re-circulating flow system while it is running through a heat

exchanger to enhance heat transfer and then dissolve the surfactants back into solution to reduce drag. Like with many solutions, it is possible to force the precipitation of surfactants by decreasing the temperature of the solution or by increasing the shear forces in the flow system [13]. However, one unique quality of the zwittercationic solution used in this study is the fact that it exhibits a rare phenomenon called dilution precipitation [12]. This means that after the micelles are sufficiently dissolved in solution, it is actually possible to cause the micelles to precipitate by adding solvent. Previous studies with this peculiar zwittercationic solution have involved creating phase diagrams to determine at what concentration the zwittercationic micelles would precipitate out of solution if water was slowly added [12]. One such phase diagram is included in Figure 3 [12].

1.5:1

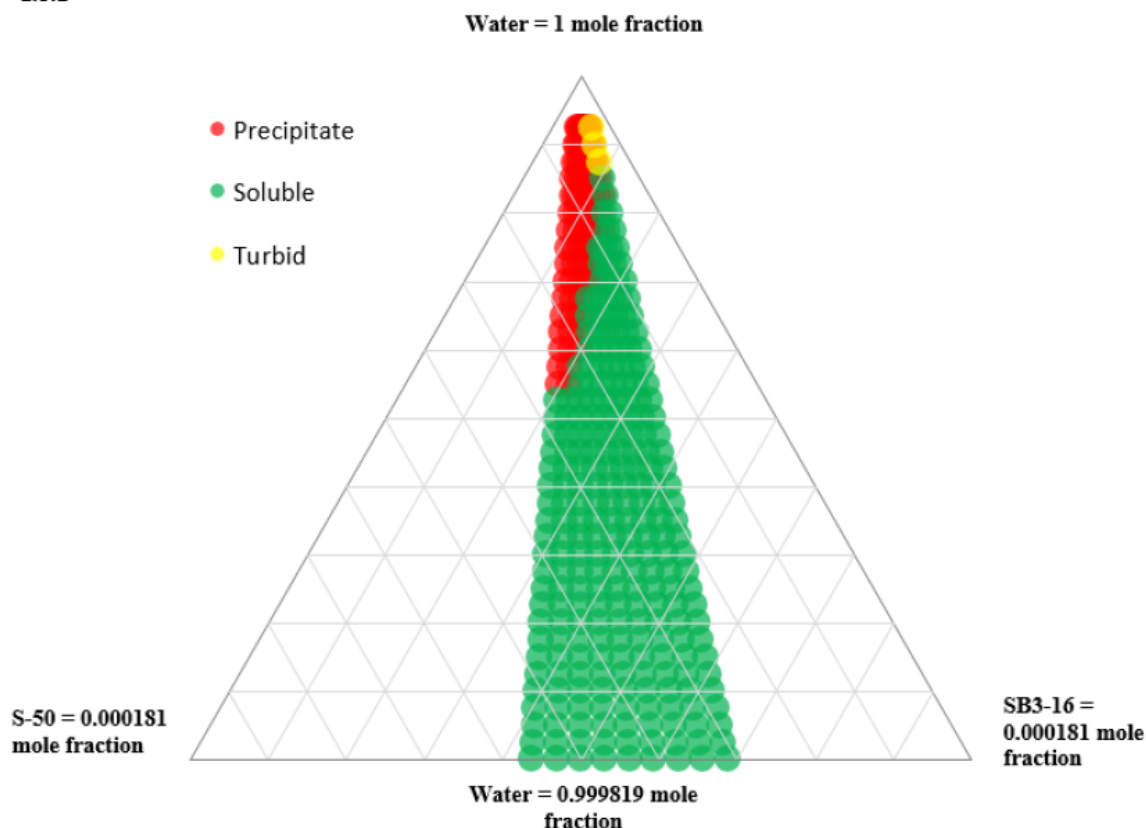


Figure 3: Phase diagram showing the dilution precipitation of the zwittercationic solution

1.7 Research Significance

Due to the unique dilution precipitation quality of the zwittercationic solution, this solution allows for the opportunity to see if concentration change is a viable method for enhancing heat transfer in a district heating or cooling system that uses drag reducing additives with similar properties. Theoretically, a zwittercationic solution at a concentration that is on the edge of dilution precipitation could have a small amount of water added before the use of a heat exchanger in order to enhance heat transfer and then some method for removing a small amount of water, such as reverse osmosis, could be used to help the surfactant micelles back into solution after the heat exchanger for drag reduction. This research seeks to prove that the use of reverse osmosis in drag-reducing solutions that exhibit dilution precipitation could be a viable method for enhancing transfer while decreasing pumping costs in district heating and cooling systems while also noting any potential drawbacks for this method that would not have otherwise been noticed.

2 Materials and Methods

2.1 Surfactants Used

The solution used for this study used two different kinds of surfactants and a counterion. The first surfactant used was 3-(N,N-Dimethylpalmitylammonio)-propanesulfonate, also known as SB3-16. It is a zwitterionic surfactant with a molecular weight of 391.66 g/mol. The chemical structure of SB3-16 can be seen in Figure 4 [12].

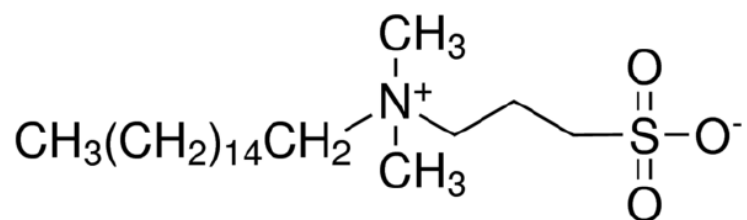


Figure 4: SB3-16 Chemical Structure

The second surfactant used to create the drag reducing solution for this study was Arquad S-50. It is a cationic surfactant with an average molecular weight of 430.00 g/mol. The chemical structure of Arquad S-50 can be seen in Figure 5 [12].

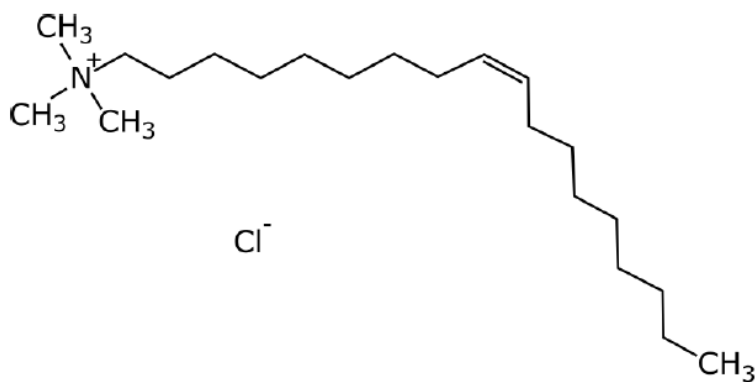


Figure 5: Arquad S-50 Chemical Structure

Finally, the counterion used in this study's drag reducing solution was sodium salicylate (NaSal). It has a molecular weight of 160.11 g/mol, and its chemical structure can be seen in Figure 6 [12].

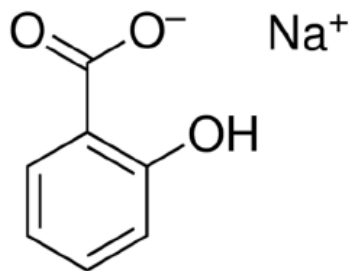


Figure 6: Sodium Salicylate Chemical Structure

These two surfactants and the sodium salicylate counterion were mixed with DI water to create the drag-reducing solution used in the experiment.

2.2 Initial Solution Concentration

For this study, the desired solution concentration was one such that the surfactants were at a high enough concentration to be drag reducing but at a low enough concentration to be easily precipitated out of solution with just a small addition of water. Based on recent work with this zwittercationic solution, an initial 500 mL batch was made with 2.13 mM SB3-16 and 2.87 mM Arquad S-50 (5 mM total surfactant) balanced with 10 mM of sodium salicylate for a 2:1 ratio of counterion to surfactant [14]. From here, a 50 mL aliquot of this solution was used to test for the concentration at which the surfactant micelles would precipitate out of the solution. 1 mL of DI water was added to the 50 mL sample at a time. If the micelles precipitated out, the solution would be heated to as high as 30°C and allowed to mix for at least one day to make sure that the precipitate did not go back into solution. The micelles were on the edge of staying precipitated when the the concentration was decreased to 4.384 mM of surfactant. For this reason, one 10 L batch and a smaller 500 mL batch of the zwittercationic solution was made to be used in the study with 1.864 mM of SB3-16 and 2.520 mM of Arquad S-50 (4.384 mM surfactant) as well as 8.768 mM of sodium salicylate to maintain the 2:1 ratio of counterion to surfactant. It was observed

that at this concentration, even the slightest shearing would cause the surfactant micelles to precipitate before quickly going back into solution.

2.3 Initial Reverse Osmosis Experiment

Before testing the 10 L batch of zwittercationic solution in a laboratory scale re-circulating flow system, the 500 mL batch was tested by itself with a reverse osmosis system. For this small experiment, the 500 mL zwittercationic solution was first diluted with 10 mL of water so that the surfactant micelles would precipitate. Then, a BP-1530 booster pump from Growonix was used to transfer the solution through a Growonix GX200 reverse osmosis system at approximately 70 psi with the concentrated surfactant solution and the clean water from the reverse osmosis system going to two separate containers. The concentrated zwittercationic solution was then observed to see if the reverse osmosis system was able to recreate a drag-reducing solution with no precipitate. The two primary things that were looked for in the re-concentrated solution were a lack of precipitate, and recoil of the solution upon stirring, which indicates that the solution is probably drag reducing.

2.4 Recirculating Flow System Experiments

To find how concentration affected drag reduction and heat transfer reduction in the zwittercationic solution, the recirculating flow system shown in Figure 7 was used.

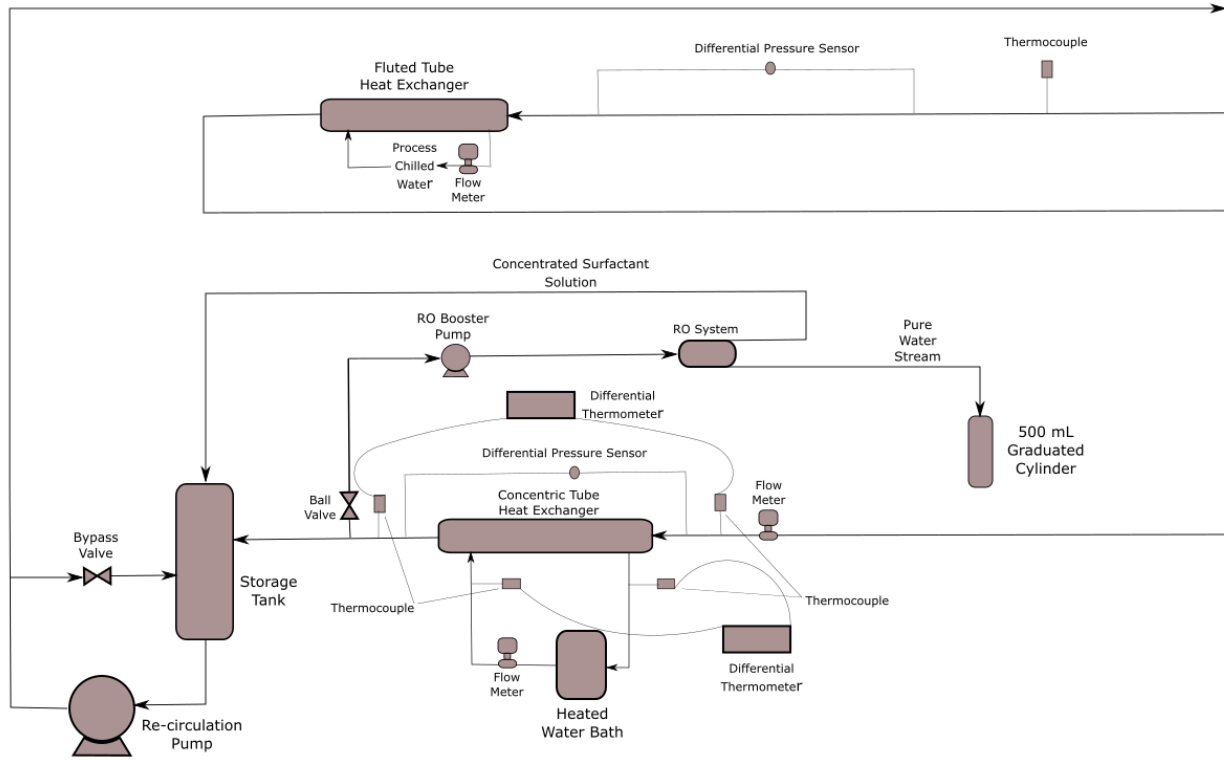


Figure 7: Recirculating Flow System (Not to Scale)

This flow system was approximately 20 meters in length which included a section where drag reduction would be measured with an Omega PX2300 differential pressure sensor used in conjunction with a DaqBoard 2000 data acquisition board, a fluted tube heat exchanger used for cooling the system if necessary to bring temperature to a steady state, and a concentric tube heat exchanger where a hot water stream and a BAT-10 differential thermometer with electrically isolated T-type thermocouples were used to measure heat transfer reduction. After the concentric tube heat exchanger, the system split into two paths: one path that went immediately back to the storage tank to circulate through the system again and one path with a ball valve that went through a GX200 reverse osmosis membrane. If the ball valve was shut, all of the solution would continuously re-circulate through the system. However, if the ball valve was open, some of the stream would be concentrated in the reverse osmosis system before re-circulating, and pure water from the

reverse osmosis system would be collected in a 500 mL graduated cylinder.

Tests started with the 10 L batch of 5mM surfactant and 2:1 counterion ratio zwittercationic solution and no flow to the reverse osmosis system. Drag reduction and heat transfer reduction were measured at this concentration for at least 4 different Reynolds numbers: approximately 20000, 28000, 35000, and 40000. The flow rates for these tests were randomized by using the random number generator and sort functions in Excel. Once DR and HTR were measured at a given concentration, then 200 mL of DI water was added to the system, and the process was repeated until drag and heat transfer reduction were no longer evident. Once drag reduction and heat transfer reduction disappeared, the ball valve to the reverse osmosis system was opened and water would be taken out of the system. Drag reduction and heat transfer reduction measurements were then taken for these more concentrated solutions before taking more water out of the system. No more water was taken out of the system once the amount of water taken out was equal to the amount of water added to the system, meaning that the solution was supposedly back at the original 10 L and 5 mM of surfactant with a 2:1 counterion ratio.

2.4.1 Drag Reduction Calibration

To determine the drag reduction caused by the surfactant micelles, a differential pressure sensor was used in conjunction with a data acquisition board to determine the pressure drop in the flow system. To calibrate the pressure drop readings, a Toshiba LF404 electromagnetic flowmeter was used to determine the volumetric flow rate of water in the flow system at various pumping speeds. From the volumetric flow rate, the flow velocity was able to be determined with the cross-sectional area of the pipe via Equation 4.

$$u = \frac{V}{A} \quad (4)$$

From here, with the known viscosity and density of water along with the pipe diameter, the Reynolds number of the fluid flow was able to be calculate via Equation 5.

$$Re = \frac{\rho u D}{\mu} \quad (5)$$

This Reynolds number can then be used in conjunction with the Von Kármán equation, shown in Equation 6 to determine the Fanning friction factor.

$$\frac{1}{\sqrt{f}} = 0.86 \ln(Re \sqrt{f}) - 0.8 \quad (6)$$

Finally, pressure drop can be calculated from the friction factor, fluid density, linear velocity, pipe length, and pipe radius by Equation 7.

$$\Delta P = f \frac{L}{R} \rho u^2 \quad (7)$$

By calculating the pressure drop for various flow rates of water, a graph can be made of the pressure drop versus the voltage signal output from the differential pressure sensor. This forms a linear graph that can be used for interpolating the pressure drop values at other voltage outputs.

2.4.2 Heat Transfer Reduction Calibration

In addition to calibrating the drag reduction readings, water was used in the flow system to calibrate the heat transfer reduction readings too. As described by Equation 2, the heat transfer reduction is described by the percent decrease in the Nusselt number due to the onset of drag reduction. The Nusselt number can be defined by the relationship between the convective heat transfer, h , the hydraulic diameter, D , and the thermal conductivity of the fluid, k , as shown in Equation 8, which is known as the Dittus-Boelter equation.

$$Nu = \frac{hD}{k} \quad (8)$$

In this experiment, the diameter and thermal conductivity were considered to be the same for both the solvent and the drag reducing solution. Therefore, for the purposes of

this experiment, heat transfer reduction can actually be defined by Equation 9.

$$HTR\% = \frac{h_{solvent} - h_{measured}}{h_{solvent}} * 100\% \quad (9)$$

This means that the readings for convective heat transfer, h , were the values that actually needed to be calibrated with water before starting the experiment. For this purpose, a modified Wilson plot method was used in which a three parameter exponential fit, as shown in Equation 10, was used.

$$q = ae^{(\frac{b}{c+Re})} \quad (10)$$

By fitting the three parameters (a , b , and c) from this equation to the heat transfer rate, q , found for water at different Reynolds numbers, other q values could be interpolated from a calibration curve, which could then be used to determine the convective heat transfer.

3 Results and Discussion

3.1 Initial Reverse Osmosis Experiment

Before running the zwittercationic solution through a re-circulating flow system, the reverse osmosis system was tested with a 500 mL batch of the 4.384 M zwittercationic solution. The 500 mL batch was diluted by 10 mL of DI water to 4.298 M, causing the micelles to precipitate out of the solution, which would theoretically take away its drag-reducing properties. Then, the solution was pumped through the reverse osmosis system at 70 psi with one outlet for pure water and one outlet for the concentrated solution. The goal was to concentrate the solution enough for the micelles to come back into the solution, allowing it to be drag-reducing again.

After pumping the solution through the reverse osmosis membrane, only 330 mL of solution came out of the concentrated stream and 60 mL of pure water came out of the

pure water stream. This means that there was approximately 120 mL of solution that was actually pumped into the membrane but was unaccounted for at the end of the experiment. It is theorized that the majority of this volume was trapped in the membrane.

Upon observing the re-concentrated solution, it was noticed that previously precipitated surfactant micelles had not gone back into solution. To aid the process, the solution was lightly stirred and heated to 50°C over the course of an hour. When testing solution concentrations to determine what to use for the experiment, it was observed that all of the concentrations tested no longer had precipitate after being heated to 40°C, so it was expected that there would no longer be any precipitate in the re-concentrated solution after being heated to 50°C. However, after heating and allowing the solution to sit for 1 day, the precipitate was still present. An image of the re-concentrated solution can be seen in Figure 8.

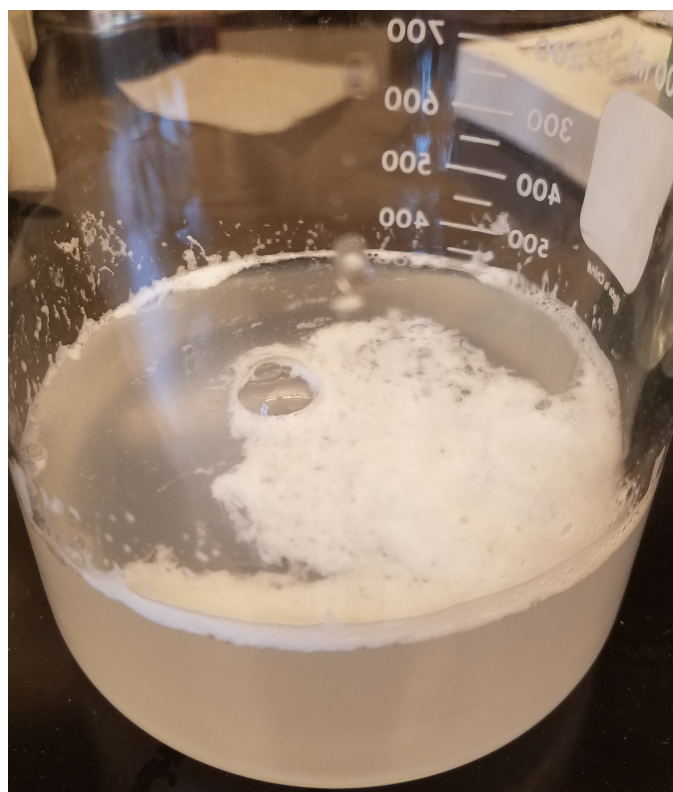


Figure 8: The Re-concentrated Zwittercationic Solution

The purpose of this miniature experiment was to determine if using the reverse osmosis system in the recirculating flow system to dilute and re-concentrate the drag-reducing zwittercationic solution would actually work. Since the precipitated micelles from the diluted solution did not come back into solution after being re-concentrated, it seemed that the re-circulating flow system was unlikely to work. Yet, it was possible that the 120 mL of solution that was trapped in the membrane was causing significant error in the results. Since all of the materials for the recirculating flow system were already available, that experiment proceeded as planned despite these results.

3.2 The Recirculating Flow Experiment

To save time, drag reduction and heat transfer reduction data was only taken at four Reynolds numbers for most concentrations tested. For consistency and to simplify the presentation of the data, any data taken at other Reynolds numbers were not included. The four Reynolds numbers tested were approximately 20000, 28000, 35000, and 40000.

The first part of this experiment was to dilute the 4.384 M surfactant solution by 200 mL, take both DR and HTR measurements, and then repeat until DR and HTR was no longer present. The DR measurements during the dilution process are shown in Figure 9, and the corresponding HTR measurements are shown in Figure 10. To simplify the graphs by eliminating redundancy, data for only every other concentration that was tested is shown.

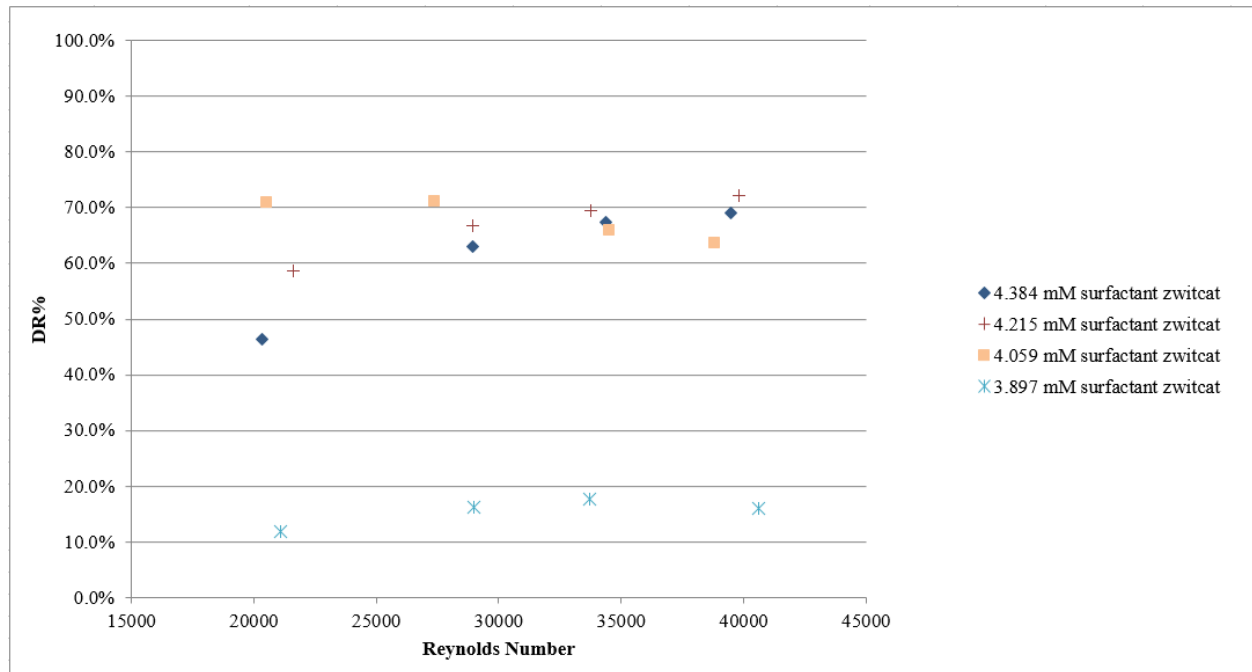


Figure 9: Percent Drag Reduction as the Solution is Diluted

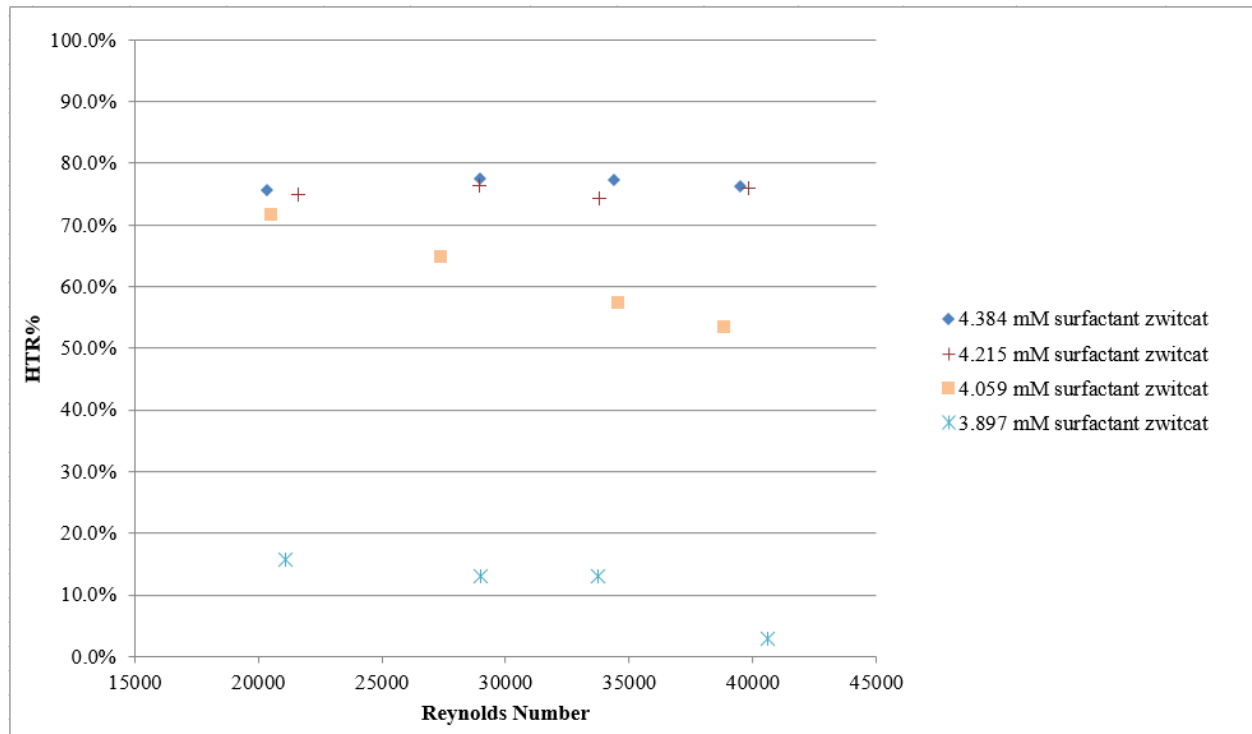


Figure 10: Percent Heat Transfer Reduction as the Solution is Diluted

From the graphs, it can be seen that DR and HTR started to decrease at higher Reynolds numbers after 800 mL of DI water was added to the original 10 L, making a 4.059 mM surfactant solution. It is theorized that the DR and HTR are lower at higher Reynolds numbers at this concentration because solution was at a concentration where increasing the flow rate would cause shear precipitation. After 1250 mL of DI water was added to the original 10 L, making a 3.897 mM surfactant solution, the DR and HTR had essentially disappeared.

For the second part of this experiment, the added water was taken out in intervals through the reverse osmosis system in an attempt to dissolve the micelles back into the solution to make it drag reducing and heat transfer reducing again. The DR measurements during the re-concentration process are shown in Figure 11, and the corresponding are shown in Figure 12.

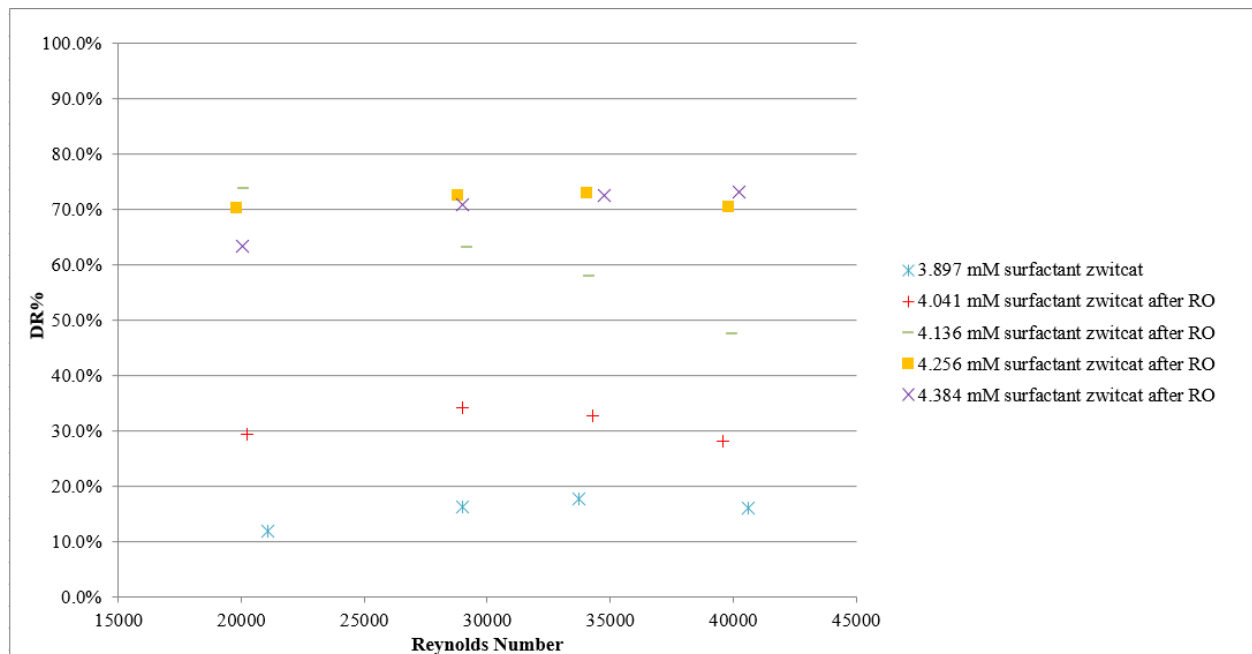


Figure 11: Percent Drag Reduction as the Solution is Re-concentrated

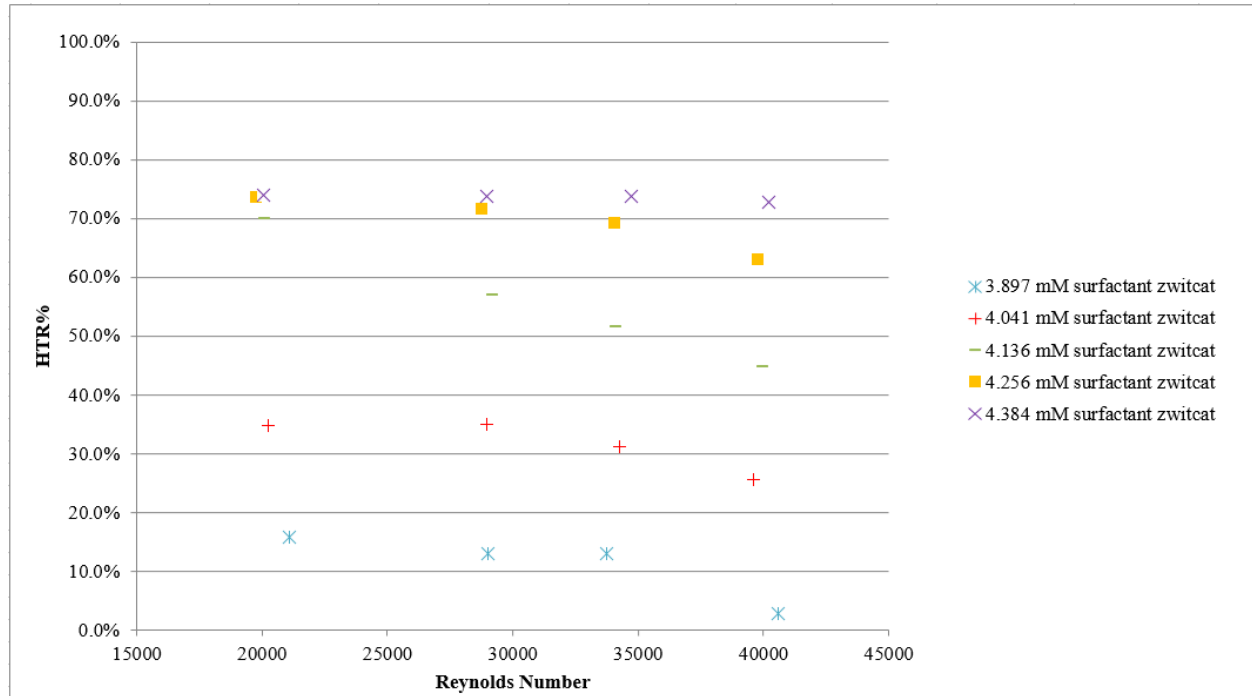


Figure 12: Percent Heat Transfer Reduction as the Solution is Re-concentrated

As can be seen by the graphs, the drag-reducing and heat-transfer reducing properties returned by the time the solution was brought back to the original concentration. It should be noted that the DR and HTR start to decrease at higher Reynolds numbers at 4.256 mM, which is a higher concentration than the 4.059 mM solution where this was evident during the dilution process. It is theorized that this is because the reverse osmosis system could be trapping some of the solution just as it did in the initial experiment with the 500 mL solution, which could be causing the recorded concentrations, which were based on the volume of water taken out through the reverse osmosis system, to be different than the actual concentration in the system. Upon removing the membrane after the experiment was over, it was noted that the volume and weight were both noticeably larger than another Growonix GX200 membrane that was unused. This implies that the some of the solution was being trapped in the membrane as had been theorized.

In order for concentration change to be a feasible method for improving heat transfer in

a drag-reducing solution in a district heating and cooling system, the ability to turn drag reduction and heat transfer reduction on and off would have to be repeatable in real time. Therefore, the next step for this experiment was to prove that it was possible to eliminate and bring back both drag and heat transfer reduction again. Figure 13 shows the drag and heat transfer reduction at 40000 Reynolds number for 4.384 mM surfactant (C) and 3.897 mM surfactant (D) in the order that the solution was diluted and re-concentrated. Any negative values are not shown since the solution should not be possible since the surfactants should not be making the heat transfer greater than that of water.

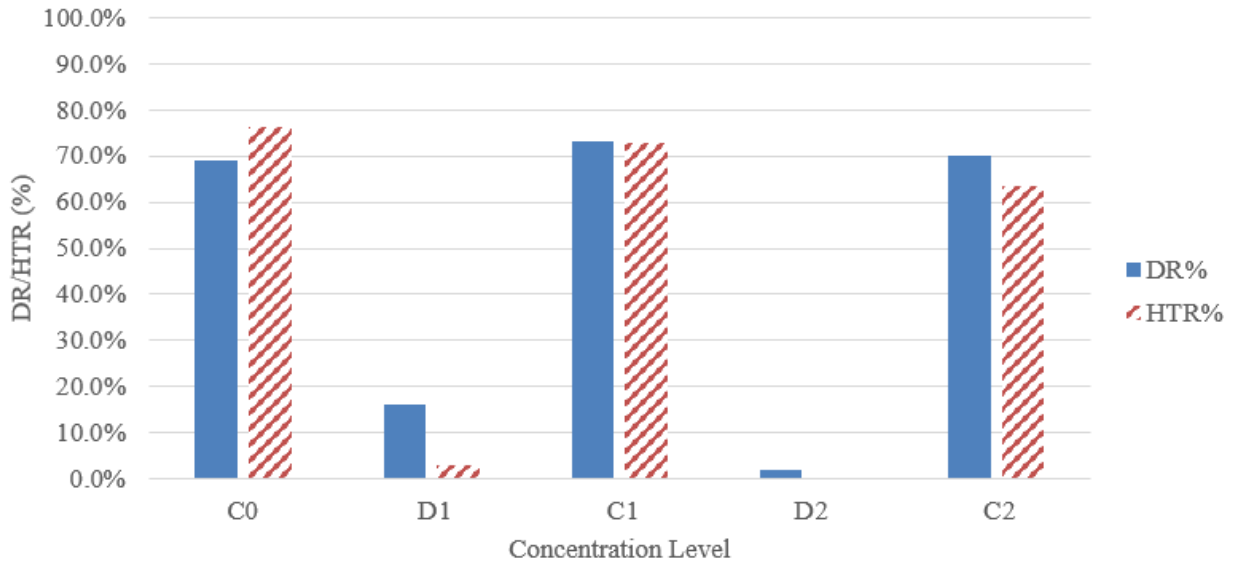


Figure 13: DR and HTR for the Concentrated (C) and Diluted (D) Zwittercationic Solution at 40000 Reynolds Number

The graph shows that the drag reduction and heat transfer reduction caused by micelles was able to be successfully turned on and off with the same amount of water being added and then taken out of solution. This implies that it may be possible to use concentration change in a similar solution to enhance heat transfer in a district heating or cooling system.

4 Conclusion and Recommendations

4.1 Conclusion

After diluting and re-concentrating a drag-reducing solution that exhibits dilution precipitation, it was shown that it is possible to eliminate and bring back drag and heat transfer reduction for the zwittercationic solution used in this experiment. It was also shown that the water necessary to cause dilution precipitation in this solution could be removed with a reverse osmosis system and then added back multiple times to cause drag and heat transfer reduction to turn on and off as desired. This ability to change the concentration to turn drag and heat transfer reduction on and off could be useful in a district heating or cooling system that would need optimal heat transfer as well as drag reduction for inexpensive pumping of the fluid.

4.2 Recommendations and Future Work

While this research has shown that it is possible to change the concentration of a solution with dilution precipitation to turn drag and heat transfer reduction on and off repeatedly, a district heating or cooling system would have to be able to do this in real time without human interaction between each dilution and concentration phase. For this purpose, the next step for this research would be to create a lab scale flow system that concentrates an already precipitated zwittercationic solution directly after a heat exchanger and then dilutes the solution with the water previously removed directly after a of piping that measures the drag reduction. If drag reduction is evident in the DR section of this system but heat transfer reduction is not evident in the heat exchanger, this would help show that concentration change is a feasible method for improving heat transfer in district heating or cooling systems. It was originally planned to run a real time experiment with the system used in this experiment, but due to time constraints and difficulties putting precipitated

micelles back into solution outside of the recirculating flow system, this was not tested. Ideally, the flow system for this experiment would be larger than the one used for this experiment so that the micelles would have more time to come back into solution.

In addition to this, it would be interesting to investigate why the micelles in the initial small-scale experiment never went back into solution. If it was because the membrane was trapping some of the solution, it would be interesting to see if there is a point where the membrane no longer works because of this. Additionally, it would be interesting to run an IR spectroscopy test on the clean water stream from this experiment to determine how well the membrane is separating clean water from the solution.

Finally, the biggest problem associated with using this system for a real-world application is that the reverse osmosis membrane used in this experiment, along with many other membranes, degrades over time when exposed to chlorine ions. This presents a problem because Arquad S-50 has a chlorine ion in its structure to balance out the cationic charge of the surfactant. For this experiment, this problem was ignored since the membrane only needed to work for the duration of the experiment, but a real-world application would need a membrane that is able to endure repeated use. It would be necessary to find either a membrane that can resist these ions or a different surfactant solution without chlorine ions that also exhibits dilution precipitation.

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